

On a Balanced Delta Robot for Precise Aerial Manipulation: Implementation, Testing, and Lessons for Future Designs

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Abstract—Using a delta-manipulator for stabilisation of an end-effector to perform precise spatial positioning is a current area of interest in aerial manipulation. High speed precision movements of a manipulator can cause disturbances to the aerial platform, which hinders trajectory tracking and in some cases could be sufficient to cause a loss of control of the vehicle. In this paper, a statically balanced delta aerial manipulator is developed and evaluated. The system is balanced using three counter-masses to reduce the force imparted onto the base and thus reduce perturbations to the movement of the drone. The system is thoroughly tested following trajectories while mounted to a force sensor and while on-board an aerial vehicle. Results show that the forces transmitted to the base in all axes are reduced considerably, however improvements in overall flight accuracy are not observed in aerial settings. Design lessons to make a balanced delta-manipulator viable for practical implementation on an aerial vehicle are discussed in depth. A video summarising the flight testing results is available at <https://youtu.be/fXKnosnVKck>.

I. INTRODUCTION

Using aerial vehicles to perform manipulation tasks is an area of current interest [1], [2], [3]. Unlike a ground based manipulator, aerial vehicles have a workspace limited only by their flight range and are agnostic to terrain conditions. A system consisting of a UAV with a robotic arm attached is sometimes known as a UAM (unmanned aerial manipulator) [4]. The arm can be utilised to provide additional degrees of actuation, grasp and manipulate objects or in some cases improve the spacial positioning accuracy of the system [5]. A significant limitation with this approach is that robotic arms, especially those with high degrees of freedom, are usually heavy and produce great dynamic effects onto the base to which they are attached [6].

For example, from Suarez A. et al. [7], to achieve high-DoF dual arm manipulation significant weight savings were necessary in their design to minimise the inertia of the arms. As the total momentum of the UAV-plus-manipulator system must be conserved, a large change in the momentum of



Fig. 1. The balanced delta manipulator during flight testing.

the manipulator will cause the UAV to move such that the momentum of the system is conserved. This movement of the UAV means that the accuracy of the manipulator will be limited, and it even risks causing damage to the UAV should significant perturbations on the flight trajectory occur.

Compensation for centre of mass changes for serial manipulators on aerial vehicles has been explored in literature. Solutions have included simple counterbalancing for manipulators with limited degrees of freedom [8], motorised moving counterweights [9], mechanical balancing [10], lightweight construction [11] (which can be combined with moving counterweights [12]) and modelling and control utilising the aerial base [13]. Control solutions have included calculation of the inertial changes of the manipulator to provide compensation, such as by computation of the manipulator dynamics [14], more complex adaptive controllers [15], [16], [17] and closed loop control using on-board cameras to track and provide the necessary trajectory corrections [18].

The use of a delta manipulator to stabilise the motion of an underactuated multirotor system has been explored in literature [19] [20]. Bodie Et al. has expanded on this concept by combining it with an omni-directional platform and exploring methods of improving the system with external wrench estimation to account for forces exerted on the drone as the arm moves rapidly [21]. In order to maximise end-

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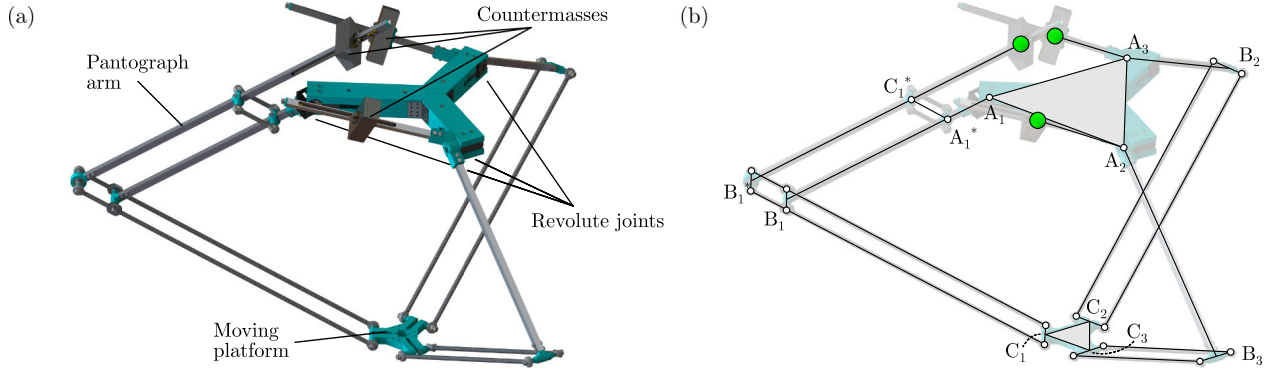


Fig. 2. Diagram of the balanced delta architecture: (a) Labelled CAD model of the balanced delta architecture, and (b) delta robot architecture overlaid the CAD model.

effector precision, the manipulator must move as fast as possible to cancel out high frequency disturbances. However, this will cause greater momentum changes and perturb the platform more severely. Although this can be compensated through force estimation and control on the multirotor side, there will always be some time delay between detection of the perturbation and making the required correction. Modelling the forces and torques exerted by the manipulator in real time and at high frequency could also become computationally costly. A mechanical solution which cancels out the perturbations due to movement of the manipulator will act instantaneously and has zero computational cost.

A manipulator designed to minimise (or ideally reduce to zero) forces transmitted to its base is described as a statically balanced system. Although the balancing of mechanisms is historically a longstanding research topic, the balancing of parallel mechanisms hadn't received significant attention until recent decades. In [22], the static balancing of planar 1, 2, and 3-DoF parallel mechanisms is investigated, and the balancing conditions are derived. A method of dynamically balancing planar 3-DoF mechanisms is presented in [23] which involves constructing the legs of the mechanism using balanced four-bar linkages. In [24], a dynamically balanced 3-DoF planar parallel robot is presented which utilises balanced five-bar parallelogram linkages for its legs. An important aspect of the design of this mechanism, along with many other balanced mechanism, is the use of the dynamic equivalence between the platform and multiple point masses; which is discussed in detail in [25]. A design and optimisation of a planar 3-DoF mechanism is detailed in [26] and a prototype is presented. In [27], the design of dynamically balanced 3 and 6-DoF mechanisms is presented through the use of balanced parallel-piped mechanisms. The force balancing conditions of Clavel's delta robot are presented in [28]. Various methods of dynamically balancing mechanisms are evaluated in [29] in terms of the amount of mass each method adds to the system. The method of synthesising dynamically balanced mechanisms through the use of counter-rotary counter-mass double pendula is presented in [29]. A combination of balanced five-bar linkages and counter-rotary mechanisms are employed in [30] for the dynamic balancing

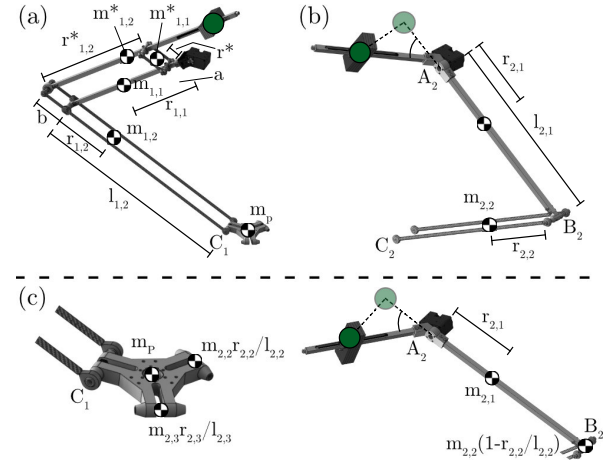


Fig. 3. Mass position parameters of the (a) 3D-pantograph counter-mass arm and (b) offset counter-mass arm, and (c) mass modelling to evaluate each arm individually.

of a kinematically redundant planar parallel robot. The design and implementation of a dynamically balanced 4-RRR parallel mechanism is presented in [31]. The majority of the works detailed above make theoretical contributions in terms of the derivation of balancing conditions for various parallel mechanisms, and the methods of designing such mechanisms. However, the number of mechanisms that have been physically implemented is limited, especially when it comes to balanced spatial manipulators. In this paper, the design and construction of a large statically balanced 3-DoF delta robot is presented and flight tested. The main contribution of the presented work is the mechanical design of a statically balanced delta robot such that it can be fixed to a UAV, and it is the authors' hope that the lessons learnt from the process will aid any future designs of similar systems. The rest of the paper is structured as follows. In section II, the architecture of the manipulator is presented and the balancing conditions are given. The mechanical implementation of the manipulator is discussed in section III, and in section IV the experimental setup for evaluating the balancing performance of the manipulator is described, the results of which are discussed in section V. Finally, in section VI we conclude.

II. BALANCED DELTA ROBOT ARCHITECTURE

The manipulator uses a delta-type parallel robot architecture to control the position of the end-effector; the structure of this architecture is shown in Fig. 2. The end-effector is connected to the base via three limbs. The proximal link of each limb is connected to the base via an actuated revolute joint. A pair of links are connected between each proximal link and the end-effector via a spherical joint at each end. The end-effector can move with three degrees of freedom; it can translate in the X , Y , and Z axes and moves with a constant orientation.

A statically balanced manipulator exerts no force onto the base for any motion of the end-effector. In order to achieve the static balancing of the manipulator, it must be designed such that the total linear momentum is constant for any motion of the end-effector. The most practical way of achieving this is by designing the system such that the linear momentum is always equal to zero, which implies the position of the centre of mass of the manipulator must be constant. This is achieved by adding a system of counter-masses to the manipulator, and calibrating their positions and masses such that the centre of mass remains in the same position for any trajectory of the end-effector. For a delta-type architecture, moment balancing is not achievable using passively driven counter-mass elements [28]. It is possible to achieve moment balancing through a control-based solution, but this is beyond the scope of this paper.

Fig. 2 shows the kinematic architecture of the robot along with the system of counter-masses which are used to force balance the mechanism. The method of balancing is based on that presented in-theory in [28]. Since the orientation of the end-effector of the delta robot is constant for any trajectory, the entire mechanism can be balanced using only three counter-masses, and one pantograph linkage. Two of the counter-masses are attached directly to the proximal links of two of the arms of the mechanism. The third counter-mass is attached to the pantograph linkage, and it is used to balance the mass of its corresponding proximal link, and also the mass of the end-effector. There are other methods of force balancing the mechanism, for example attaching a counter-mass to every proximal and distal link. The method shown in Fig. 2 was selected as it only requires three counter-masses, all of which are relatively close to the base.

The counter-mass systems used on each of the three limbs are shown in more detail in Fig. 3; from herein the limb to which the pantograph is attached is referred to as limb 1, and the others as limbs 2 and 3. Limbs 2 and 3 only require a single counter-mass attached to their respective proximal links in order to balance the mass of the proximal link and part of the mass of the distal link. Comparatively, the counter-mass attached to the pantograph not only balances the mass of the proximal and distal links of link 1, but also the mass of the end-effector and parts of the masses of the distal links of limbs 2 and 3. The notation used to denote the centre of mass of each of the rigid components of each limb, and the distances from the joints to which they are

TABLE I
PARAMETERS OF THE STATICALLY BALANCED DELTA MANIPULATOR

Parameter	Value	Units
$l_{1,1}, l_{2,1}, l_{3,1}$	0.4254	m
$l_{1,2}, l_{2,2}, l_{3,2}$	0.5454	m
$m_{1,1}$	0.1506	kg
$m_{1,2}$	0.1026	kg
$m_{1,1}^*$	0.0128	kg
$m_{1,2}^*$	1.4590	kg
$m_{2,1}, m_{3,1}$	0.3902	kg
$m_{2,2}, m_{3,2}$	0.0429	kg
m_P	0.1281	kg
$r_{1,1}$	0.2148	m
$r_{1,2}$	0.1826	m
$r_{1,1}^*$	0.0382	m
$r_{1,2}^*$	0.5286	m
$r_{2,1}, r_{3,1}$	-0.0234	m
$r_{2,2}, r_{3,2}$	0.2727	m
a	0.1344	m
b	0.0764	m

attached, are detailed in Fig. 3. The position of the counter-masses is also shown, highlighting the minor addition of the angular offset to the masses for limbs 2 and 3. In order for the mechanism to be statically balanced, the positions and masses of the counter-masses must be selected such that the total linear momentum of the system is zero, regardless of the joint velocities of the mechanism. By modelling the system as a set of point masses corresponding to each rigid component of the mechanism, the total linear momentum of the system can be formulated in terms of the dimensions of these components, their masses, and the joint velocities of the mechanism. The set of conditions that must be met for a balanced system are then obtained by collecting the coefficients of the joint velocities, and equating them to zero. The balancing conditions that are necessary to statically balance the mechanism are given in equations (1-4). For the sake of brevity, the derivation of these equations is not given here, but it is detailed in full in [28].

$$m_{1,1}r_{1,1} + m_{1,2}l_{1,1} + m_{1,1}^*a + m_{1,2}^*(l_{1,1} - r_{1,2}^*) \quad (1)$$

$$+ (m_P + \frac{r_{2,2}}{l_{2,2}}m_{2,2} + \frac{r_{3,2}}{l_{3,2}}m_{3,2})l_{1,1} = 0$$

$$m_{1,2}r_{1,2} - m_{1,1}^*r_{1,1}^* - m_{1,2}^*b + \quad (2)$$

$$(m_P + \frac{r_{2,2}}{l_{2,2}}m_{2,2} + \frac{r_{3,2}}{l_{3,2}}m_{3,2})l_{1,2} = 0$$

$$m_{2,1}r_{2,1} + \frac{l_{2,2} - r_{2,2}}{l_{2,2}}m_{2,2}l_{2,1} = 0 \quad (3)$$

$$m_{3,1}r_{3,1} + \frac{l_{3,2} - r_{3,2}}{l_{3,2}}m_{3,2}l_{3,1} = 0 \quad (4)$$

As long as equations (1-4) hold, the total linear momentum of the manipulator will be zero for any motion of the end-effector. Before the dimensions of the counter-masses were determined, the lengths of the links and the dimensions of the base and end-effector were selected such that a reasonable end-effector workspace was achievable. Firstly, the distances at which the counter-masses could be positioned from their respective motors were limited by the the potential of colliding with body of the UAV, and so these dimensions were

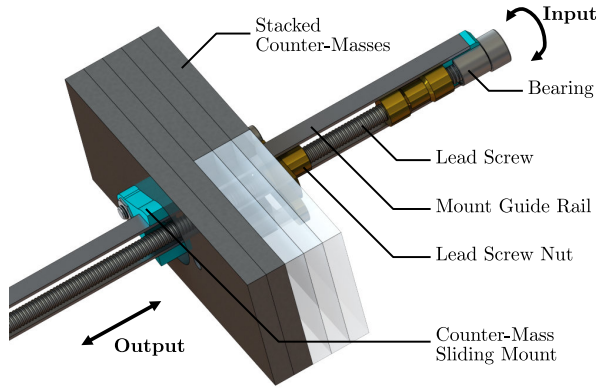


Fig. 4. CAD model cutaway of the adjustable mass system, which allows variable and accurate positioning of the counterweight. The sliding mount can further be removed from the square profile to vary the stacked counterweight masses.

selected to be as large as possible whilst avoiding the risk of collisions. For limbs 2 and 3, this corresponds to the determination of lengths $r_{2,1}$ and $r_{3,1}$, respectively. With the positions of the counterweights selected, their masses were found by solving equations (3) and (4) for $m_{2,1}$ and $m_{3,1}$, respectively, as all of the other dimensions in each equation are known. Similarly for limb 1, many of the dimensions were determined by the spatial constraints, and the mass of the counter-mass, $m_{1,2}^*$, was found by solving equations (1) and (2). The selected values for the dimensions, and the corresponding masses and their positions, can be seen in Table I.

III. MANIPULATOR DESIGN

The balanced delta manipulator structure was formed primarily using 12mm square aluminium profiles for the proximal links and 8mm carbon fibre rods for the distal links. 3D printed components (material Prusament ABS), shown in teal colour in Fig. 2(a), along with spherical bearings (Fluro GAXS6) with a maximum pivot angle of 13° were used to connect the links of the manipulator together. The remainder of the components of the manipulator (such as spherical bearing housings or couplings) were machined out of steel and brass. The key dimensions of the delta manipulator were 425.4mm for the proximal link length and 545.4mm for the distal link length. Three XH540-W270 Dynamixel motors, connected in series, were used to control the positioning of the arms, with a single motor positioned at the top of each of the primary links (positions A_1 , A_2 , and A_3 in Fig. 2). As described in Section II, two types of delta limbs were developed: A simple arm with a typical counter-mass, and a more complex arm using a pantograph mechanism attached to a counter-mass. For the simple arms, the counter-mass was attached directly to the other side of the motor such that it balanced the majority of their connected proximal and distal links. This counter-mass was connected at an offset angle, shown in Fig. 3(b), to prevent the occurrence of self collisions with the motor housing and frame connecting the manipulator to the drone. For the pantograph arm, the

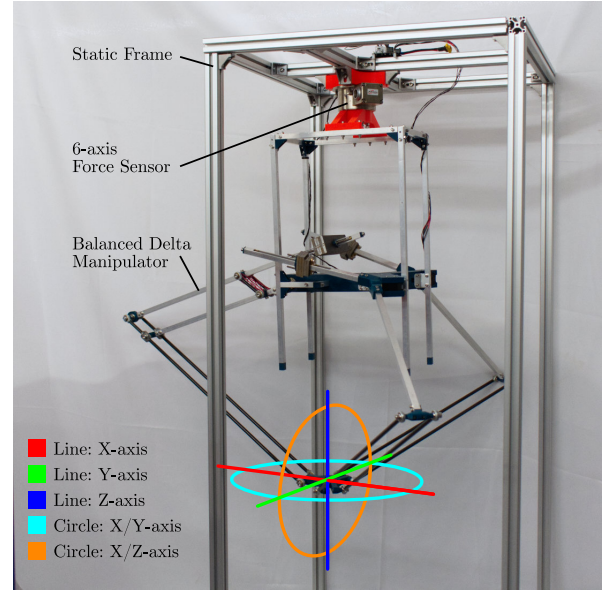


Fig. 5. The balanced delta robot manipulator mounted to a force-torque sensor within a static rigid testing rig. The 5 tested trajectories are also shown.

counter-mass was instead attached to a separate aluminium profile, offset from the proximal link using four smaller carbon fibre rods. Attached to the middle of the proximal link, these are connected using rod end bearings. At the end of the proximal link, these are connected directly to the distal link as an extension of the distal link.

A. Adjustable counter-mass system

For the counter-masses it was expected that, due to manufacturing limitations, it would be difficult to position them accurately. A mass system was therefore developed to allow for easy and accurate adjustment of the position of the counter-masses along their respective links. The counter-masses were formed using stacks of stainless steel sheets bolted together, which could be removed or replaced to achieve any desired mass. These were then attached to a sliding mount on the counter-mass arms, of which the position could be adjusted using a lead screw running along the length of the counter-mass arm through the mount. The lead screw rotation was controlled using a hex socket directly connected to it at the end of the arm, using a hex tool. A detailed diagram showing the adjustable system is in Fig. 4.

B. Drone attachment and landing support

To offset the delta manipulator from the drone a support frame was developed that placed the arm 360mm below the drone, using similar materials (aluminium profiles and printed joints) to the manipulator arm. This was to ensure the counter-masses did not interact with the structure and blades of the drone. This frame can be observed in Fig. 5 between the force sensor and manipulator. Furthermore, the frame was extended beyond the manipulator so that, when the manipulator was stowed for take off and landing, the

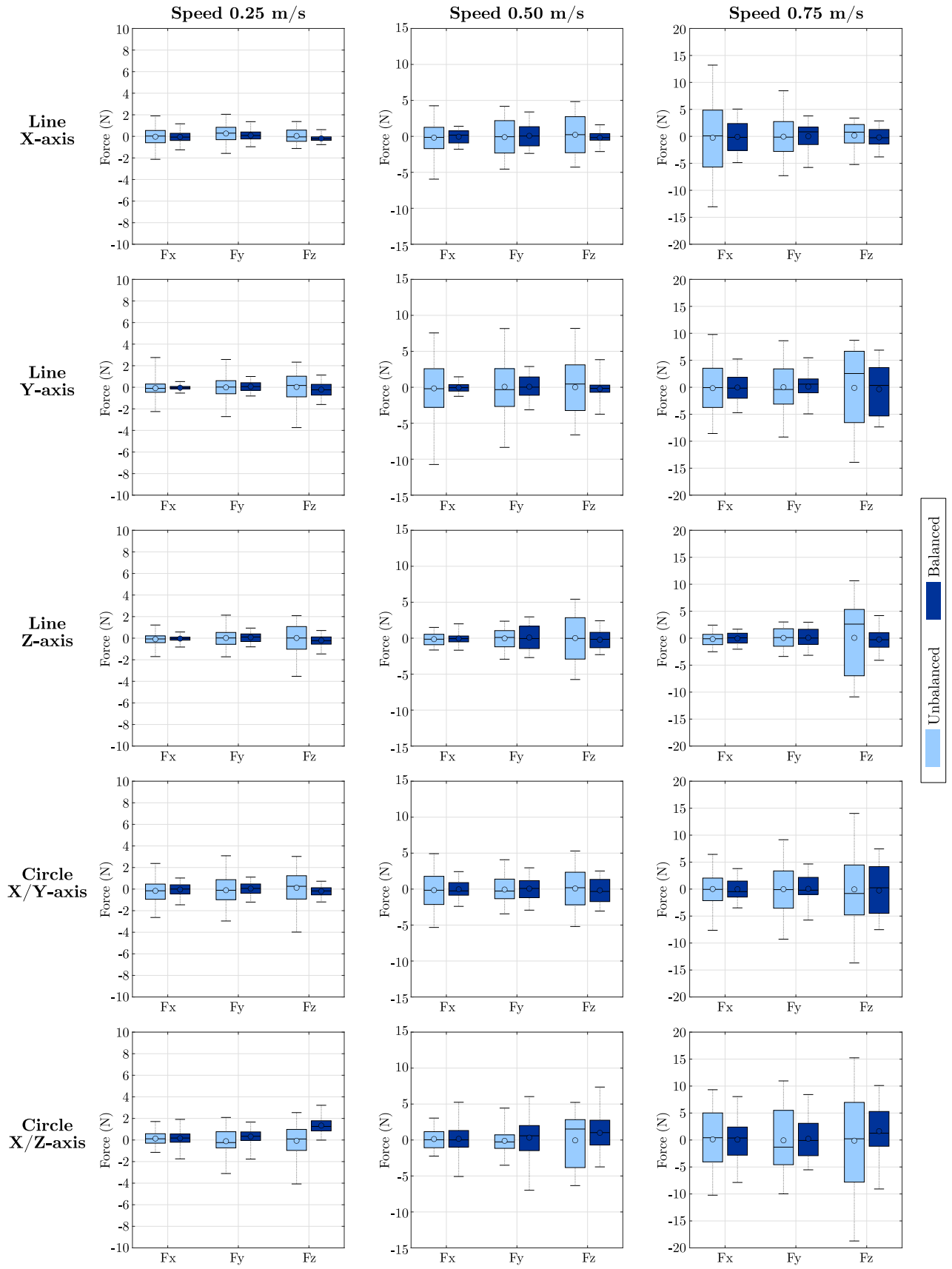


Fig. 6. Box plots indicating the distribution of forces imposed on the force sensor during static testing, where **light blue** is the unbalanced manipulator and **dark blue** is the balanced manipulator. Line trajectories in the three coordinate axes are performed, as well as circular trajectories in the $X - Y$ and $X - Z$ planes. Trajectories are shown at three speeds: 0.25 m/s, 0.50 m/s, and 0.75 m/s.

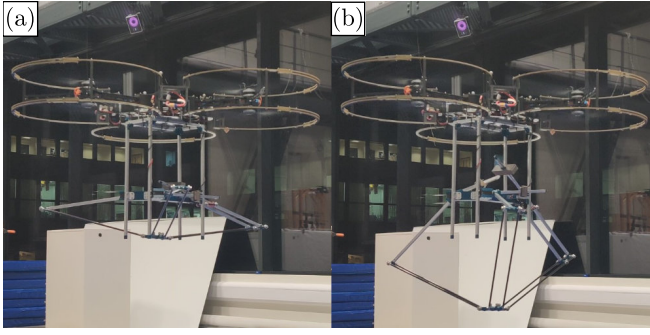


Fig. 7. The balanced delta manipulator is designed to stow for take-off/landing with a protective frame preventing ground contact with the manipulator. (a) The stowed manipulator and (b) the deployed manipulator during flight.

frame could be used as landing gear. This was done to prevent damage to both the manipulator and drone during these flight operations due to their significant combined weight. The manipulator in stowed and deployed position can be seen in Fig. 7, and the computed workspaces of the end effector and counter-masses with respect to the drone can be seen in Fig. 8.

IV. EXPERIMENTAL EVALUATION

The balancing performance of the manipulator was assessed by measuring the balancing forces imparted onto the base for a range of motions of the end-effector. These results are compared with that of an ‘unbalanced’ version of the manipulator for which the counter-masses are removed. In both cases the manipulator was attached to a static frame formed of aluminium profiles, via an ATI Gamma IP65 force-torque sensor. The static experimental setup is shown in Fig. 5. The forces imparted onto the base were then measured for five different trajectories of the end-effector; two circular trajectories in the $X-Y$ plane and $X-Z$ plane, and three linear trajectories along the X , Y , and Z axes. A diagram of the five trajectories with respect to the manipulator is shown in Fig. 5. The X , Y , and Z axes make a right-handed coordinate system where the Z -axis is normal to the plane formed by the three motors and the X -axis is defined by the vector from the centre point of the three motors to the motor which drives the pantograph linkage. For the linear motion, a sinusoidal velocity profile was used, where the maximum speed achieved during the profile was the requested speed. For the circular trajectories, a constant speed at the requested value of the end effector was used. The five trajectories were carried out at three different speeds of 0.25 m/s, 0.50 m/s, and 0.75 m/s. The results can be seen in Fig. 6, showing the measured forces for each of the trajectories.

The manipulator was then tested following the same circular trajectories as those tested on the force balance while in flight on-board a hovering aerial vehicle. The aerial platform is described in Orr Et al. [32], which includes details of the flight performance and a list of components. The gains of the default Pixhawk P/PID multicopter position controller were tuned initially with a 6kg simulated payload (comprised

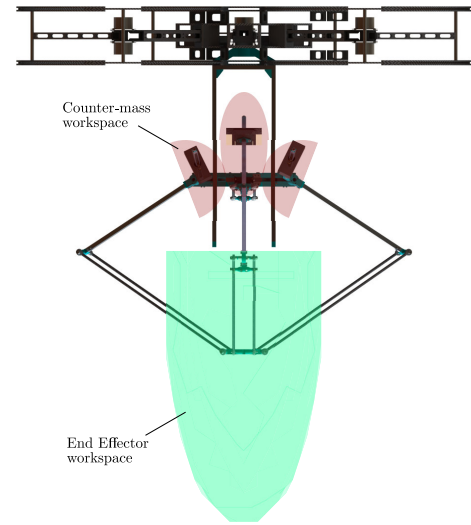


Fig. 8. The balanced delta manipulator mounted on the drone, highlighting the calculated manipulator workspace (**green**) and counter-mass workspaces (**red**).

of aluminium billet) and were not adjusted between tests. Position feedback was provided by a Vicon motion capture system. The motion capture data was recorded to obtain trajectory tracking errors for the body of the drone and for the end-effector of the manipulator. The manipulator was moved in a 10cm radius circle for 10 cycles at 0.5m/s. This trajectory was repeated in the $x-z$ and $x-y$ planes with and without the counterweights. The trajectories for the drone and the manipulator were provided in the frame of the tracking arena, such that the manipulator was required to follow the trajectories while also attempting to compensate for perturbations to the body of the drone. The results of this experiment are shown in Fig. 9.

V. DISCUSSION AND DESIGN LESSONS

From the results shown in Fig. 6 we see a reduction in all trajectories, for all axes, with varying ranges of reduction with the addition of the balancing system, leading to a reduction in the shaking forces felt at the base. Across the three speeds evaluated, there was observed, on average, an increase in experienced forces with an increase in end effector speed. Interestingly, this did not increase equally across all axes. For example, F_z in the Line Z-axis showed a significant increase with speed, whereas the other axes F_x and F_y had only a minor increase.

For the vertical trajectory along the Line Z-axis, major reductions in force were experienced only in the F_z axis, where the balanced manipulator performed much better than the unbalanced manipulator, especially at the higher end-effector velocity. For the Line X-axis trajectory, significant reductions in force were seen in the F_x and F_z axes for the 0.25 and 0.5m/s speeds, while F_y and F_z showed strong reductions at 0.75m/s. For the Line Y-axis, similar reductions across all axes in all speeds were seen.

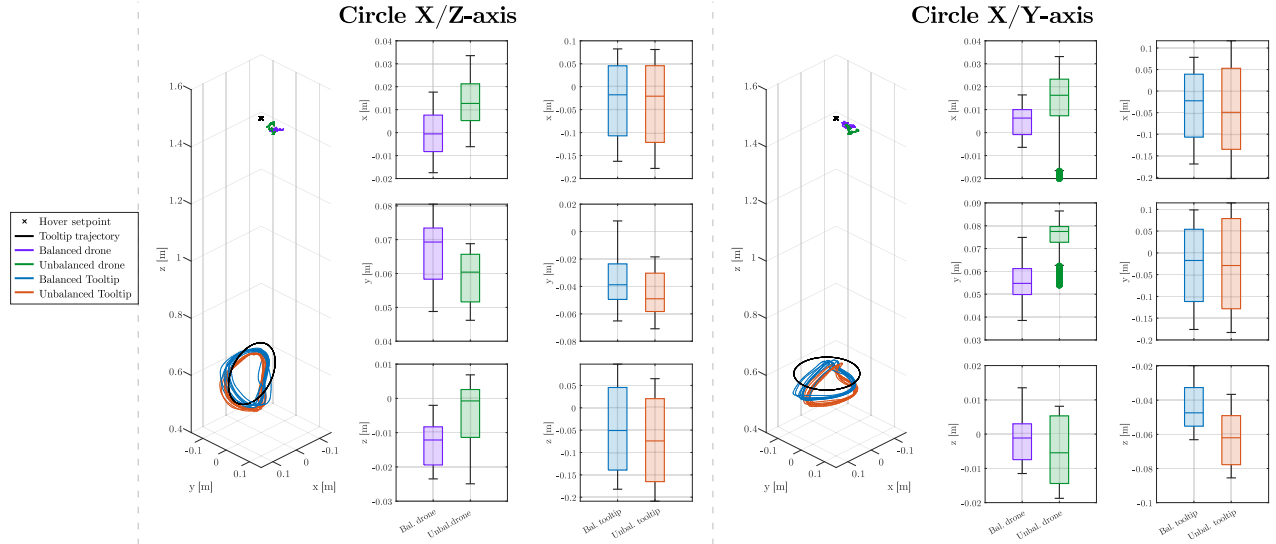


Fig. 9. In-flight motion tracking results for the aerial vehicle and end effector for the X-Z circle trajectory (left) and X-Y circle trajectory (right).

From these linear trajectories, the least significant reduction in force was observed for the F_y axis. This is likely due to the complexity in the design of the pantograph linkage, specifically the shorter links connecting A_1^* and C_1^* which have to support the high weight of the pantograph counter mass (see Fig. 2 for notation). A significant challenge in the design of this mechanism was achieving accurate relative positioning of the pantograph counter mass to the end effector, predominantly with-respect-to motion along the Y-axis, which likely caused the more limited improvements of the balanced system for motions of the end-effector along the Y-axis. Indeed, it can be seen that the results along the X and Z axes do not experience these same issues, and the reduction in the shaking force is much more significant.

For the Circle X/Y-axis, reductions in force were again seen across all axes and all speeds, whereas for the Circle X/Z-axis only minor reductions in force, if any, were seen, with the 0.5m/s speed actually showing increased experienced forces for the balanced system. This was to be expected, as the circular trajectories predictably should show combinations of the force reductions shown in the corresponding linear trajectories. Hence, the X-Y circle trajectory shows reductions across all axes, whereas the X-Z circle only significantly shows a reduction in the F_z axis.

Overall the static testing results demonstrate that at higher speeds, where more extreme forces are imparted on the mount, the implementation of a balancing system provides more consequential gains. On average, the balancing system is successful at reducing the experienced forces across all axes at all tested speeds, with the most notable reductions in the F_x and F_z axes.

The flight testing results, presented in Figure 9, have not demonstrated a significant improvement in performance on-board a real system. Marginal improvements in the range of trajectory tracking errors can be seen in some axes, however this could also be attributed to random variation in

performance within margin of error. As the intention when designing the manipulator was to showcase the benefits of balancing, the system was made as large as possible to maximise perturbations. However, the system is also heavy and the vehicle has a low thrust-to-weight ratio when in flight ($\approx 75\%$). The additional mass of the counterweights impacts this further. This reduces the ability of the system to counter-act perturbations and may outweigh the benefits of balancing; the trade-off between the reduction in shaking forces and additional mass is certainly an important consideration.

In order to make a balanced delta-manipulator viable for practical implementation on an aerial vehicle, a number of design changes would be required. The UAV platform used here was not initially built to be integrated with the statically balanced delta robot, and hence there are multiple design choices that could be made if the UAV platform were to be developed alongside the manipulator. The performance impact of carrying counterweights could be countered by replacing the steel masses with a functional component such as batteries to run auxiliary systems, thus eliminating the increase in take off mass. The manipulator base must be stood off considerably from the body of the drone to make space for the counterweight linkages, which increases the moment of inertia of the body and severely impacts rolling and pitching performance. A dedicated airframe to accommodate the manipulator could include cutouts for the counter-masses, or alternatively the three-way symmetry of the coaxial tricopter layout could be utilised to mount the manipulator around the exterior of the vehicle, with the counterweights above the system and the arm linkages below. The developed manipulator is also very large relative to the size of the system. This was an intentional decision to showcase the benefits of balancing, however a smaller manipulator with a workspace sufficient only to counter random perturbations and provide stabilisation (approximately 5cm^3) could be made significantly smaller and lighter.

VI. CONCLUSION

This work presents the design of a force-balanced delta manipulator for aerial manipulation. The architecture of the delta robot is described, along with the design and construction of a physical implementation highlighting the unique structure and adjustable counter-mass positioning system. Static testing of the developed manipulator demonstrates a significant reduction of the imparted forces onto the robot mount, specifically for the x and z axes, with minor reductions in the y axis. Dynamic testing on an aerial vehicle however does not show a significant improvement, at least in terms of overall flight accuracy, and the reasoning behind this is discussed in depth. Future designs incorporating the changes discussed could facilitate higher precision end-effector stabilisation without requiring additional control considerations for the vehicle.

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